Crack Detection in Armor Plates Using Ultrasonic Techniques

by Thomas J. Meitzler[1], Gregory Smith[1], Michelle Charbeneau[1], Euijung Sohn[1], Mary Bienkowski[1], Ivan Wong[1] and Allen H. Meitzler[2]

ABSTRACT

A method of using piezoelectric lead zirconate titanate (PZT) transducers to characterize the vibrational modes of ceramic Vehicle Body Armor Support System (VBASS) plates for the purpose of crack detection is presented. The amplitudes of the vibrational modes of undamaged plates are compared to the vibrational mode amplitudes of damaged plates and are shown to be clearly different. VBASS plates for testing are damaged either by a blunt impact to the ceramic plate surface or cracked using a machine-shop press. Data from these tests will be used to design a prototype hand-held device for the nondestructive testing (NDT) of the VBASS plate structural integrity. VBASS plates are used as proof-of-principle samples in the absence of vest body armor samples.

Keywords: *ceramic armor plates, NDT, PZT transducers, crack detection*

INTRODUCTION

Various types of Silicon Carbide (SiC) composite body armor plates are in use by the US military because of the relative light weight and the degree of ballistic protection offered to soldiers by ceramic plates. Obviously, the protection is diminished if the plate integrity is compromised. Any number of things can induce cracks in the SiC plates; therefore it is important to inspect them after manufacturing, prior to shipping, and most importantly, in the field. There are various methods to inspect VBASS plates using a fixed laboratory based device [1]; however, these techniques are clearly not available in the field.

To achieve the goal of developing a portable test device, the authors used PZT transducers to excite flexural mode waves in the VBASS ceramic armor plates. The resulting transmission signals were used to characterize the plates and for later application in device development.

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The authors found that there is a clear difference in the transmission signal between damaged and undamaged plates. Figure 1 below shows the structural composition of a damaged ceramic VBASS plate.

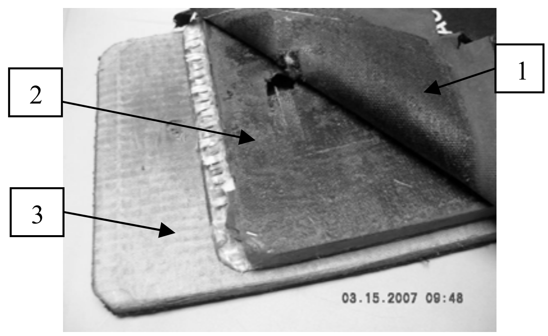

Figure 1- Structure of a damaged VBASS plate

As shown in Figure 1 above, VBASS plates have three basic components to them; 1) an outer canvas layer, 2) a ceramic impact plate placed in the middle, and 3) a composite inner layer intended to contain the high energy fragments from the impact of a round. The authors are using VBASS plates as a material to test the efficacy of various prototypes of a hand-held device to inspect the plates for cracks. It is envisioned that a hand-held device could be used to perform plate inspection in the field, away from a laboratory-based inspection system. The goal of such field testing is not to determine the location of a crack but to provide a go/no-go test of the integrity of the armor plate. Initially, a baseline measurement of the undamaged plate vibration data obtained in a laboratory environment will be stored in the hand-held device for later reference in the field.

METHODOLOGY

To maximize the contact between the piezoelectric PZT transducers and the plate, a small area of the canvas is removed along with a thin layer of the adhesive used to keep the canvas attached to the plate. PZT transducers are then bonded to the two ends of the ceramic plate using standard consumer grade epoxy as is shown in Figure 2. An alternating voltage is applied to the driving piezoelectric transducer on the left in Figure 2 causing it to vibrate. This movement excites a mechanical wave in the

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plate which forces the receiving transducer on the right to vibrate and generate voltages via the piezoelectric effect. These signals are observed using an oscilloscope. The basic method of this technique is to use the signal generator to sweep through a frequency range of a few hundred kHz to characterize the response of an undamaged plate and then to use that data as a baseline to determine the condition of other plates that are suspected of being damaged. In our particular test design, a LabVIEW^{TM} program was written to control the sweep of the signal generator through various frequencies and to record the output voltage from the transducer attached on the opposing end of the plate.

resemblance to the driving waveform. These differences in both amplitude and shape of the signals generated at the receiving transducers clearly indicate different plate vibrational resonances indicating a damaged plate.

Figure 4 shows the graph of the peak-to peak output voltages from the receiving transducer of the three VBASS plates. One plate is undamaged, the second contains a small area of impact damage, and the third contains a hairline crack across the plate. The dramatic reduction in the received amplitude is a clear indication of plate damage.

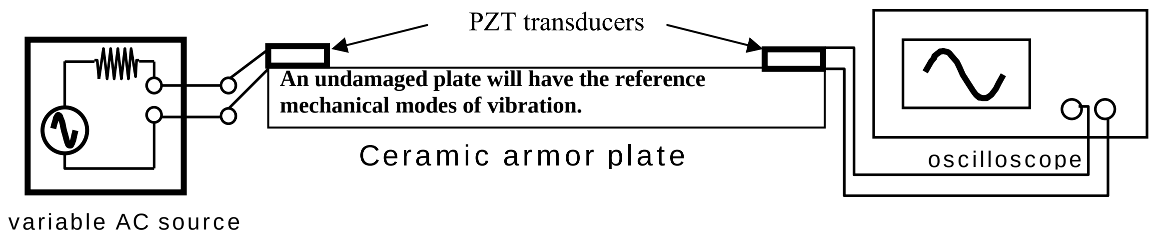

Figure 2 - Schematic of the test circuit with a ceramic plate

DATA

VBASS plates were damaged in three ways and then analyzed with the aforementioned program-directed scanning technique. Two modes of damage were studied: blunt impact damage and crack damage induced by a hydraulic press. The plates were also imaged using an in-house x-ray machine used for NDT. Damage to the plate subject to blunt impact was barely detectable on x-ray. The press induced crack was clearly visible.

A. PZT Transducer Resonant Frequency Location

The fundamental frequency of the PZT transducers used to determine the ceramic plate vibration mode flexural frequencies was determined using a Wayne-Kerr admittance bridge, an oscilloscope and a signal generator. The bridge is manually adjusted to produce a balance condition. Usually, but not always, this test is performed by the manufacturer of the transducers as part of a quality control process.

B. Plate Resonant Frequency Location

Figure 3 is an oscillogram showing the voltage amplitudes of the undamaged and cracked plate under test. The top-most trace is the signal of 63 kHz applied to driving transducer on both plates. The center trace is the signal from the receiving transducer on the undamaged plate. While it is diminished in amplitude and contains slightly more noise the only significant difference from the driving signal is a 2.5 µsec phase delay due to transmission delay through the plate. The bottom trace is the signal from the receiving transducer on the cracked plate. This waveform is extremely low in amplitude and bares little

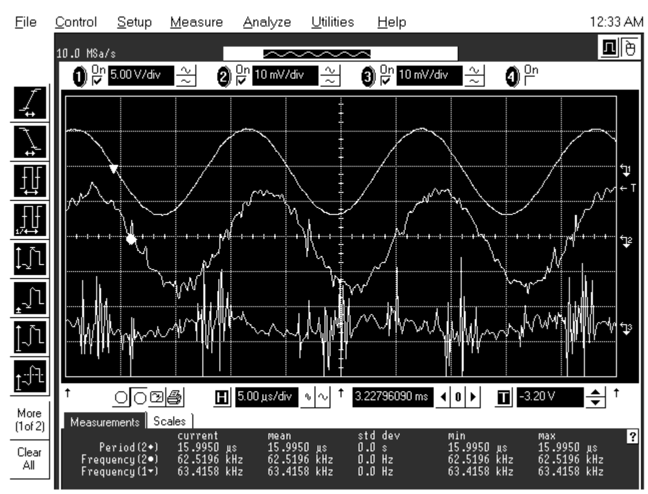

Figure 3 - Oscillogram of input and output voltages on cracked plate

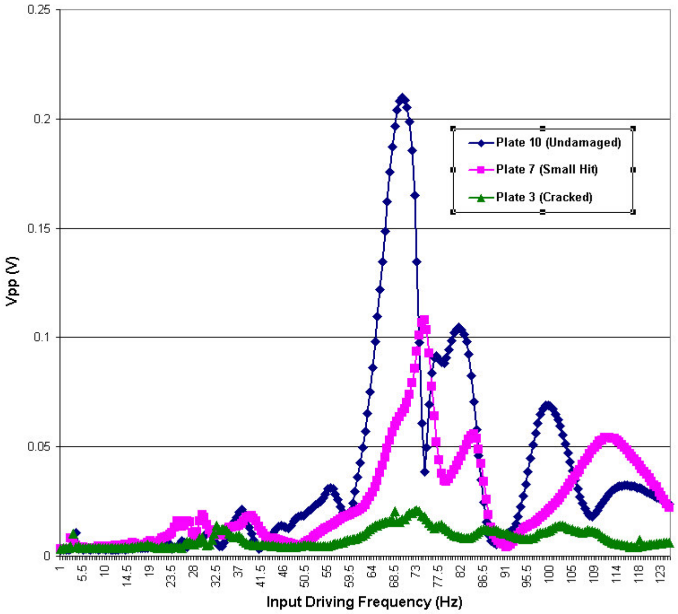

Figure 4– Plots of the output peak-to-peak voltages of the VBASS plates for the three different conditions

A second metric the authors used to compare the plates was the total harmonic distortion of the received signals. The THD is defined below in Equation 1 as:

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \ldots + V_n^2}}{V_1} \qquad (1)$$

Where V_n are the n'th harmonics of the peak-to-peak voltages measured .

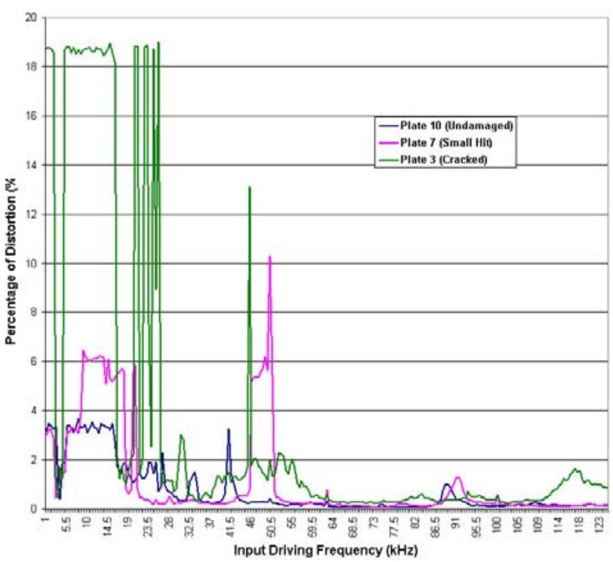

Figure 5 – Plots of the total harmonic distortion of the output voltages

Figure 5 shows a graph of the THD versus input driving frequency. As expected from inspection of the oscillogram traces, the THD is lowest for the undamaged plate, higher for the plate containing small blunt impact damage and significantly higher for the cracked plate.

In order to attain the goal of having a portable device for plate crack detection, a single transducer arrangement is the most likely design that would lead to a practical device. The authors investigated a method using a transducer to first excite the plate into resonant vibration and then switch to a receive mode to sense the resulting decaying vibrations. It was found that by applying only a few cycles (five to seven) of excitation near resonant frequencies it was possible to obtain an extremely consistent decay signal with a characteristic ellipsoidal envelop. Figures 6 and 7 illustrate this response for undamaged and damaged plates. In the oscillogram in Figures 6 and 7, the vertical axis is 50 mV/div and 10 µsec/div for the horizontal axis. Figure 6 shows waveform, or signature, of an undamaged plated that the authors to used as the reference plate response. Figure 7 shows the waveform of a damaged plate. Figure 8 illustrates the configuration used to accomplish this excite/sense decaying vibrations method. It is important to disconnect the exciting circuit during the sensing portion of the test so that the low impedance output of the exciting circuit does not load down the sensor thereby reducing its response.

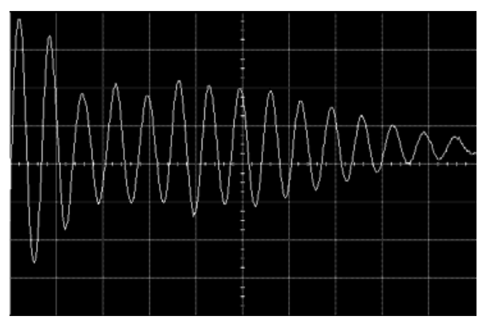

Figure 6 – Decaying vibrations of undamaged plate

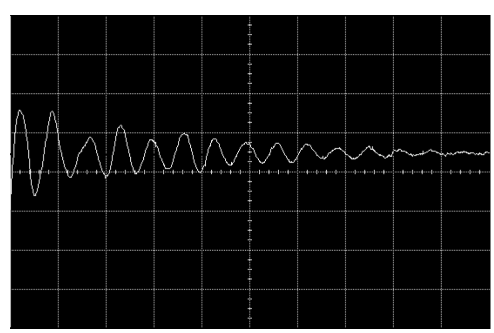

Figure 7 – Decaying vibrations of cracked plate

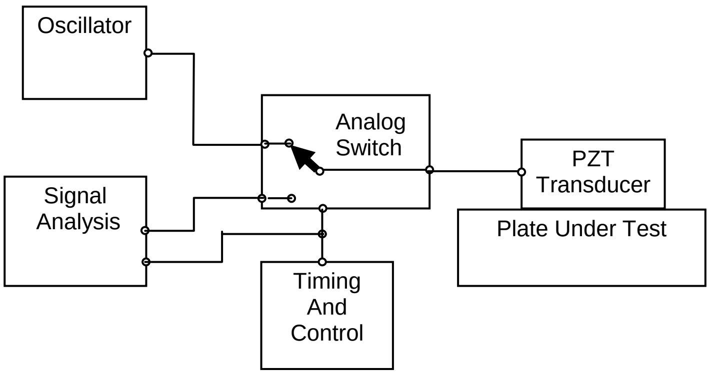

Figure 8 – Block diagram of the electronic system for Exciting/Sensing decaying vibrations of a cracked plate

ANALYSIS

The natural vibration mode frequencies of the plate under study were computed and compared to the measurements made with the PZT transducers. Calling "w" the plate vertical displacement, the equation of motion for a plate under various boundary conditions is derived by Leissa [2, 7] and is,

$$D\nabla^2 w + \rho \frac{d^2 w}{dt^2} = 0, \tag{2}$$

where D is the plate stiffness defined by,

$$D = \frac{Eh^3}{12(1-\nu^2)}, \tag{3}$$

where E is Young's modulus, h is the plate thickness, ν is Poisson's ratio, ρ is the mass density per unit area of the plate, ∇^2 is the three-dimensional Laplacian operator, and t is the time. A table of the constants and physical dimensions of the plate that are used in the computation of the resonant frequencies, shown in equation (4), are provided below in Table I. In equation (4), m and n, are the integers representing the vibrational modes for the length and width respectively. The solutions to the equation of motion are the frequencies of vibration, ω, of the plate and are graphed in Figure 9. As can be seen in the chart of Figure 9, there are groups of resonant frequencies approximately every twenty kHz.

$$\omega_{mn} = \sqrt{\frac{D}{\rho}\left\{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2\right\}} \tag{4}$$

In Figure 9 the group of frequencies around 70 kHz corresponds with the fundamental resonant frequency of the PZT transducer at 69 KHz which was determined from admittance measurements of unbonded transducers as discussed earlier. Differences between the computed and measured resonance frequency values can be explained by the fact that the theory is for a monolithic plate and experimentally we made the measurements with a three layered plate as is shown in Fig. 1. In progress, are efforts to implement a numerical, multi-layer model of ultrasound transmission in layered media. The ability to simulate ultrasonic non-destructive testing will make the development and testing of various transducer designs more efficient.

TABLE I: PHYSICAL CONSTANT AND PLATE VALUES [3]

Young's Modulus	401.38 GPa
Poisson's Ratio	0.1875
Density	4303 kg/m^3
Plate Dimensions	
Plate length, a	33 cm
Plate width, b	17.8 cm
Plate depth, d	2.4 cm
Volume	660 cm^3

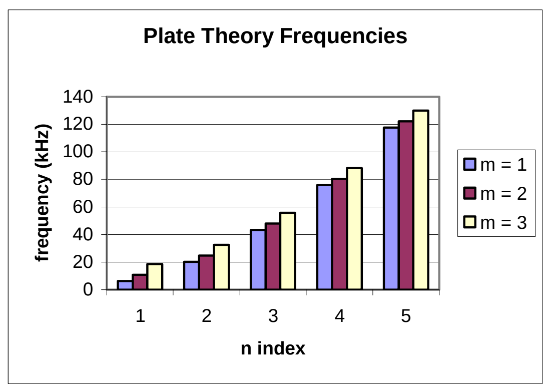

Figure 9: Chart of computed resonant frequencies of the VBASS plate

FUTURE EFFORTS

One of the goals of this research is to develop a device that can test for the existence of cracks in armor plates in the field, away from laboratories or test equipment. The prototype device is based on the "impact method" and a schematic of the prototype is shown in Fig. 10. (An excellent review of the ultrasonic "impact method" is provided in the Evans [4] patent as well as other texts on NDT [5,6].) This device would be held over the armor sample and pushed against the plate to release the plunger. This action will send a shockwave through the plate which can be picked up by a ring transducer inside the device for measurement and comparison. Presently the device is attached to an oscilloscope for signal analysis. In the future, it is planned to have an integrated MEMS device collect and perform the required data and signal analysis. The use of a piezoelectric transducer as both the exciter and sensor is also possible in a hand held device and this configuration is currently in the prototype phase.

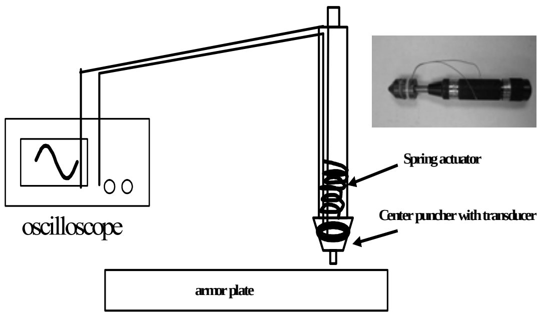

Figure 10: Hand-held "impact method" prototype

CONCLUSIONS

PZT transducers can be used to characterize the flexural mode resonances of rectangular, ceramic armor plates in a range of frequencies between 50 and 100 kHz. By the use of bonded transducers on the VBASS plate, the presence of hairline cracks can be determined by comparing the output voltage waveforms against that of an undamaged plate. The authors have shown how PZT transducers, in a variant of the impact method [4], can be used to characterize the resonant modes of vibration of a ceramic armor plate and how a single transducer can be used to distinguish damaged from undamaged plates.

Two metrics were used to determine if the plates were cracked; 1. the peak-to-peak output voltage versus frequency of the driving voltage and, 2. the total harmonic distortion of the output signal versus the input driving frequency relative to that of the uncracked plate. The peak-to-peak voltage graphs clearly show a shift in the resonant vibration frequency of the plate from 65 kHz to 74 kHz as well as a reduction in the amplitude of the transmission signal. The total harmonic distortion compliments the peak-to-peak voltage graphs by showing the degree of distortion of the transmitted signal in the cracked plate relative to the uncracked plate. The total harmonic distortion metric may be useful in the future to determine crack depth or severity.

The ultimate objective of this work is to develop a device that provides a reliable cracked or uncracked plate assessment in the field. The authors have demonstrated a working prototype of a portable, handheld device to perform this kind of test. Based on the data from the experiments mentioned above, research and development is currently under way to develop more robust versions of the hand-held device for armor crack detection in the field.

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Thomas J. Meitzler (M ''83) was born May 5, 1955 in Allentown, PA. He obtained a B.S. and M.S. in Physics from Eastern Michigan University, attended the Univ. of Michigan, and received a Ph.D. in Electrical Engineering from Wayne State University in Detroit, MI.

Dr. Thomas Meitzler has taught Physics, Astronomy and Engineering courses at The University of Michigan-Dearborn and Henry Ford Community College. From 1988 to present he has been a research engineer at the U.S. Army Tank-Automotive Research and Development Engineering Center in Warren in the department of Survivability Technology. He has published papers on infrared and visual detection computational methods, detection probability and infrared electro-optic system simulation.

Dr. Thomas Meitzler is a co-winner of the 1995 U.S. Army Research and Development Achievement award and has several patents. His research interests include sensor and image fusion, ultrasonic non-destructive testing and imaging, functional magnetic resonance imaging, 3D- imaging technologies and high fidelity photo-simulation. He is currently involved in cooperative research efforts with NASA's Kennedy Space Center and Columbia University Medical School.

Gregory Smith graduated from the University of Michigan with a Bachelors of Science Electrical Engineering, 1968

Mr. Smith began his career doing detailed logic design of equipment to do signal processing and display for major DOD contractors. In 1976 he went to work for The Ford Motor Company as a Research Engineer where he was part of the team that developed the first digital computer based electronic engine control. Mr. Smith subsequently worked in emission research, manufacturing research and ended his career with Ford working in active safety research where he worked in acquisition and processing of both visible and thermal IR video data. Mr. Smith is now retired from Ford and works ½ time in the Visual Perception Laboratory at the U.S. Army Research Development and Engineering Center in Warren Michigan. Mr. Smith is Inventor or Co inventor on numerous patents in the fields of optical metrology and vehicle safety.

Primary Experience: Remote Sensing Research and Advanced Engineering. This includes concept, design, prototype build, test and evaluation for applications ranging from anti-submarine warfare to automotive active safety.

Allen H. Meitzler (M'56–SM'75–F'81–LF'94) was born December 16, 1928 in Allentown, PA. He obtained a B.S. degree in Physics from Muhlenberg College in Allentown and M.S. and Ph.D. degrees in Physics from Lehigh University in Bethlehem, PA.

He joined Bell Telephone Laboratories (now called Lucent Technologies) in October 1955 and was there as a member of the Technical Staff of Telephone Laboratories until September 1972, when he joined the Research Laboratory of the Ford Motor Co. in Dearborn, MI. He retired from Ford on January 1, 1996. Over the years, Dr. Allen Meitzler has had a strong interest in the development of IEEE standards. He chaired the Piezoelectric Standards Subcommittee over the 14-yr period taken to develop IEEE Standard 176-1978, "IEEE Standard on Piezoelectricity". He was active in the preparation of the IEEE Standard 180-1986 and chaired the Ferroelectric Standards Subcommittee when the work on that standard was brought to completion. Dr. Allen Meitzler has served the UFFC-S in a variety of positions since joining the IRE (predecessor of the IEEE) in 1955. He was the Vice- Chair (1962) and Chair (1963) of the Professional Group on Ultrasonics Engineering (the PGUE was the predecessor of the UFFC-S) and served as Secretary-Treasurer from 1965 to 1970. He is a Life Fellow of the IEEE and a Fellow of the Acoustical Society of America. Since retiring from

Ford, Dr. Meitzler has continued to be professionally active, teaching part-time undergraduate electrical engineering courses at the University of Michigan - Dearborn. In addition, he has a consulting business specializing in ultrasonic devices.

Michelle T. Charbeneau was born September 21, 1979 in Detroit, MI. She obtained an A.A.S. in Computer Networking Technology - Microsoft Option from Baker College and a B.S. in Computer Engineering from Oakland University.

She has experience with business management, computer repair, computer hardware testing and evaluation, and computer programming. She is a computer engineer currently working on programming data acquisition systems with LabVIEW at the U.S. Army Tank Automotive RDEC in Warren, MI in the department of Survivability Technology.

Ivan Wong received his bachelor's degree in computer science engineering in 2007 from the University of Michigan in Ann Arbor, Michigan.

He is currently in his third year working at the US Army Tank Automotive Command LCMC in Warren, Michigan. He came onto the Visual Perception Lab team (now known as MGV Visual Testing and Analysis) in the summer of 2005 as a summer hire where he worked on evaluating cameras in high glare situations. In 2006, he returned as a co-op student to develop software for image assessment through the use of metrics.

Euijung Sohn was born at Suwon, Korea in 1966. She immigrated to the U.S. in 1985 then she finished her high school degree in Park Ridge, IL. She studied at the University of Illinois and got her B.S. degree in Electrical Engineering in 1991. After her graduation, Mrs. Sohn was hired in Simulation department in US Army Tank Automotive Command in 1991.

Mrs. Sohn has worked as a research engineer from 1992 to present in the Survivability Technology Center. She has been involved in the validation, and verification of thermal and visual detection models and atmospheric propagation studies.

Mrs. Sohn is now involved in planning, testing, and analyzing visual perception test of military ground vehicles and commercial vehicles. She is also involved in NASA ice detection research program and target detection research using fMRI of brain activities. Mrs. Sohn has authored and co-authored technical papers in the area of infrared and visual system simulations and target detection. Mrs. Sohn was a recipient of the 1995 Army Research & Development Award for the Computational Vision Model Development for Dual-Use Applications.

Mary E. Bienkowski is a Mechanical Engineer for the MGV Visual Testing and Analysis Team (MGV-VT & A), for Survivability team of the Research Business Group (RBG), at the TARDEC-RDECOM in Warren, Michigan as of 2003. Initially, she was hired to the TARDEC's Robotics Mobility Team as an engineering co-op student and aided with the statistical analysis of user training times for the Omni-Directional Inspection System (ODIS) robots for soldier support (2003-2004). Her most recent research involves working with NASA's Kennedy Space Center (KSC) developing and analyzing non-destructive electro-optics test methods for the NASA ice debris and inspection system used for external shuttle tank, in support of the Army and NASA SAA (Space Act Agreement). She is also actively participating in the implementation of future ultrasound non-destructive assessment for body armor plates applications with TARDEC's Rapid REF Team to provide a quick inspection test method for armor deployment by determination of the structural integrity of damaged body armor plates. Additional research includes collaborative work with Dr. Joy Hirsch of the Columbia University's functional Magnetic Resonance Imaging (fMRI) Research Center for developing a rapid method of detection for stealth assessment and camouflage testing using fMRI applications. Further initiatives that she helped ruggedize the housing unit of the Panoramic Image Fusion (PIF) system in efforts of vehicle 360-degree situational awareness (SA).